Researching the change of the operating frequencies in the case of
inequality of the output voltages of the comparator within the
structure of an integrating measuring
strain gauge converter

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Abstract. One of the major errors directly influencing the metrological characteristics of the inte-
grating measuring strain gauge converter is the inequality of the output voltages of the comparator.
The current paper explores the effect of the voltages variation at the output of the comparator in the
case of a bipolar power supply of the converter. The output data is obtained by modeling the equation
of conversion in the MATLAB environment. The fore-mentioned problem is investigated assuming
up to 20% inequality of the output voltages compared to the supply voltage and a bilateral change
of the load on the strain gauges. A regression analysis is performed checking the suitability of a
linear, quadratic and cubic model. It shows that the coefficient of determination is highest for the
cubic model and relevant conclusions are made.

Keywords: comparator, converter, modeling, regression analysis, strain gauges

1 Introduction.

Strain gauges measuring converters are intended to amplify and convert the small output voltages
that are obtained in disbalance of strain gauges bridge, which is known as "Wheatstone bridge". Every
"Wheatstone bridge" consists of two or four strain gauges that are connected in half bridge or full bridge.
The output voltage is proportional to the deformation of the strain gauges sensors. Depending on the
mode of guidance (method of orientation) for bonding, the strain gauges can measure forces, moments,
weight, etc.

The transformation of the change of the strain gauges deformation into frequency deviation is done
by integrating converters working on the method of ramp right conversion. The method itself is well
known and reported by many scientists: (Шахов, 1986), (Mochizuki, 1996), (Kaliyugavaradan, 2000),
(Madhu, 2009), (Гигов, 2013), (Станков, 2014) and many others. Essential advantages of the method
are simplicity circuits and high linearity conversion. The main disadvantages are the requirements for
using high performance elements, fast operational amplifiers, and accurate selection of measurement
ranges. Therefore, there is no coincidence that most schemes of integrating converters have patent pro-	ection rights, namely (Мильченко, Романов, 1980), (Гигов, Гутников, 1981), (Гигов, Янков, 1986),
(Glimert 1994), (Василев, Громков, 2009) and many others.

Here is investigated a converter of the disbalance of the resistance of a strain gauge bridge into fre-
quency deviation; its block scheme is given in Figure 1 as well (Stoyanov, 2014).

The converter in Fig. 1 comprises as follows: integrator 4, comparator 1, strain-gauge resistive bridge
2, a differential amplifier 3 and a voltage divider 5 and 6. The power diagonal of the bridge is connected
to the output of the comparator and the common ground. Measuring is done diagonally to the
inputs of the differential amplifier DA, whose output is connected to the inverting input of the integrator
I. The output of the integrator is connected to the inverting input of the comparator C, whose non-
inverting input and output are associated with the output of the converter F.
The output frequency is determined by the following equation:

$$f = \frac{1}{T} = \frac{\beta}{4\tau_i(1-\beta)} + \frac{k_{DA}}{8\tau_i(1-\beta)} \delta R$$

(1)

where:

- $T$ – the output period of the converter;

- $\beta = \frac{R_2}{R_1 + R_2}$ – coefficient of the voltage divider;

- $k_{DA}$ – the gain of the instrumental amplifier;

- $\tau_i$ – time constant of the integrator;

- $\delta R$ – relative change of the resistance of the strain gauges load (deformation).

The proposed converter has very good metrological characteristics in bilateral change to the load. A prototype has been developed, and a patent application has been made (№111382, made on 25.01.2012). (Гагов, Станков, Стоянов, 2014).

On the basis of the main metrological characteristics of the converter, which have been received up to this moment, there is need of further analysis of the errors that determine the appearance of non-linearity and that change the output frequency (Гагов, 2013).

One of the main errors that influence directly the metrological characteristics is the inequality of the output voltage of the comparator. This leads to adding or subtracting the value of the error of the output voltage $\Delta U_{out}$ to the values of the positive or negative output voltages $U^+_{out}$ and $U^-_{out}$ [Гагов, 2013].

The values of the output voltages of the comparator $U^+_{out}$ and $U^-_{out}$ are as follows:

$$U^+_{out} = U_{out} - \Delta U_{out}$$

(2)

$$U^-_{out} = U_{out} + \Delta U_{out}$$

(3)

For the corrected period $T^*$ the following is obtained:

$$T^* = T * \left( \frac{U^+_{out} + |U^-_{out}|}{U^+_{out}} + \frac{U^-_{out} + |U^-_{out}|}{U^-_{out}} \right)$$

(4)

After substitution with 2 and 3 in 4 the following is obtained:

$$T^* = T * \left( \frac{U_{out} - \Delta U_{out} + U_{out} + \Delta U_{out}}{U_{out} - \Delta U_{out}} + \frac{U_{out} - \Delta U_{out} + U_{out} + \Delta U_{out}}{U_{out} + \Delta U_{out}} \right)$$

(5)

Here the following designation is introduced:

$$\frac{\Delta U_{out}}{U_{out}} = \delta U_{out}$$

(6)

After substitution of (6) and (5) in (1) and the conversion, the corrected output frequency $f^*$ of the equation of the conversion is obtained (7):

$$f^* = \frac{1}{T^*} = \frac{1}{T} \left( \frac{1 - \delta U^2_{out}}{1} \right) = \left( \frac{\beta}{4\tau_i(1-\beta)} + \frac{k_{DA}}{8\tau_i(1-\beta)} \delta R \right) \left(1 - \delta U^2_{out} \right)$$

(7)

where $\delta U_{out}$ is the relative error of the output voltage.
Table 1 shows the data from the change of the output frequency of the comparator in modeling the equation of conversion and the influence of error in MATLAB environment (Stoyanov, 2014). A chart is built too, and it shows the time of changing of the values under load ΔR in 0,1 Ω and voltage variation ΔU in the interval from 0 to 1V. At the output voltage of the converter 5 V, the change of 1V represents 20% of the change of the output voltage. This amendment is sufficient to research the behavior of the converter at the specified input parameters.

<table>
<thead>
<tr>
<th>ΔU</th>
<th>-0.5</th>
<th>-0.4</th>
<th>-0.3</th>
<th>-0.2</th>
<th>-0.1</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.225989</td>
<td>0.310734</td>
<td>0.39548</td>
<td>0.480226</td>
<td>0.564972</td>
<td>0.649718</td>
<td>0.734463</td>
<td>0.819209</td>
<td>0.903955</td>
<td>0.988701</td>
<td>1.073446</td>
</tr>
<tr>
<td>0.2</td>
<td>0.903955</td>
<td>1.242938</td>
<td>1.581921</td>
<td>1.920904</td>
<td>2.259887</td>
<td>2.598827</td>
<td>2.937853</td>
<td>3.276836</td>
<td>3.615819</td>
<td>3.954802</td>
<td>4.293785</td>
</tr>
<tr>
<td>0.3</td>
<td>2.033898</td>
<td>2.796611</td>
<td>3.559322</td>
<td>4.322034</td>
<td>5.084746</td>
<td>5.847458</td>
<td>6.610169</td>
<td>7.372881</td>
<td>8.135593</td>
<td>8.898305</td>
<td>9.661017</td>
</tr>
<tr>
<td>0.6</td>
<td>8.135593</td>
<td>11.18644</td>
<td>14.23729</td>
<td>17.28814</td>
<td>20.38898</td>
<td>23.38983</td>
<td>26.44068</td>
<td>29.49153</td>
<td>32.54237</td>
<td>35.59322</td>
<td>38.64407</td>
</tr>
<tr>
<td>0.7</td>
<td>11.07345</td>
<td>15.22599</td>
<td>19.37853</td>
<td>23.53107</td>
<td>27.68362</td>
<td>31.83616</td>
<td>35.98877</td>
<td>40.14124</td>
<td>44.29379</td>
<td>48.44633</td>
<td>52.59887</td>
</tr>
<tr>
<td>0.8</td>
<td>14.46328</td>
<td>19.88701</td>
<td>25.31073</td>
<td>30.73446</td>
<td>36.15819</td>
<td>41.58192</td>
<td>47.00565</td>
<td>52.42938</td>
<td>57.85311</td>
<td>63.27684</td>
<td>68.70056</td>
</tr>
<tr>
<td>0.9</td>
<td>18.30508</td>
<td>25.16949</td>
<td>32.0339</td>
<td>38.89831</td>
<td>45.76271</td>
<td>52.62712</td>
<td>59.49153</td>
<td>66.35993</td>
<td>73.22034</td>
<td>80.08475</td>
<td>86.94915</td>
</tr>
<tr>
<td>1</td>
<td>22.59887</td>
<td>31.07345</td>
<td>39.54802</td>
<td>48.0226</td>
<td>56.49718</td>
<td>64.97175</td>
<td>73.44633</td>
<td>81.9209</td>
<td>90.39548</td>
<td>98.87006</td>
<td>107.3446</td>
</tr>
</tbody>
</table>

The chart in Figure 2 shows the dependencies of the change of the output frequency on the difference of the output voltages of the comparator at a fixed disbalance.

Fig. 2. Modification of the output frequency Δf depending on the amendment to ΔU and ΔR.

The conducted modeling shows that the created simulation model of the measurement converter is highly dependent on the inequality of the absolute values of the output voltages of the comparator. The received non-linearity influences strongly the metrological characteristics of the converter.

A more precise estimate of the impact of the changing tensions could be made with the aid of mathematical statistics.

It is necessary to establish the relationship with a change of the voltage difference when working with a certain load (disbalance of the system) of the change of the output frequency. In the converter all of the control factors are quantitative, and the links between them are described and analyzed mathematically by the methods of regression analysis (Митков, 2011).

2 Main part

The object of research is presented in Fig.1. In this case there is a manageable factor x, one output parameter Y and disturbing influence ε. Since the value of the parameter Δf is formed both by ΔU and

...
disturbing factors \(w_i\), the following equation can be written:

\[
Y = \eta(x) + \varepsilon
\]  

(8)

Where: \(Y = \Delta f\)  
\(x = \Delta U\)

\(\varepsilon\) – aggregate disturbing influence, which is caused by the uncontrollable factors \(w_1, w_2, w_i\)

\(\eta(x)\) – function of the factor \(x\)

The theoretical model of the researched converter will have the following form:

\[
\Delta f = \eta(\Delta U) + \varepsilon
\]  

(9)

at \(\Delta R = \text{const.}\)

The general appearance of the regression model is selected on the base of geometric submitted experimental data. Searched regression model can be written as follows:

\[
\tilde{y} = f(x; \beta_0; \beta_1; \beta_2; \beta_i)
\]  

(10)

Where \(\beta_0; \beta_1; \beta_2; \beta_i\) are the regression coefficients and \(\tilde{y} = \eta(x)\)

It is necessary that the function \(f(x)\) be approximated to one or several functions in order to determine the most reliable regression model:

\[
\tilde{y} = f(\beta_0; \beta_1 x; \beta_2 x^2; \beta_3 x^3; \beta_i x^n)
\]  

(11)

Because of the random error \(\varepsilon\) in the experimental data and because of the final number of such data, one does not receive the exact values of the parameters \(\beta_0; \beta_1; \beta_2; \beta_i\) but their ratings \(b_0; b_1; b_2; b_3; b_i\), which are defined as experimental regression coefficients. Thereby the experimental model is obtained on the basis of the theoretical model.

\[
\hat{y} = f(x; b_0; b_1; b_2; b_3; b_i)
\]  

(12)

Where \(i = 1, 2, 3 \ldots .N\) is the number of points of the experiment

In the deduced formulas of the metrological analysis one can see that the influence of the change of the tension is of the second degree. Taking into account dependencies of mathematical modeling and type of the chart, it is expected that the presentation of the regression model \(\hat{y}\) will be a second order polynomial, nonlinear internal to the factor \(\Delta U\).

\[
\hat{y} = b_0 + b_1 x + b_2 x^2
\]  

(13)

The type of the curves of the experimental chart assumes verification of the suitability of a linear model – Formula 14, and verification of the suitability of the cube model – Formula 15.

\[
\hat{y} = b_0 + b_1 x
\]  

(14)

\[
\hat{y} = b_0 + b_1 x + b_2 x^2 + b_3 x^3
\]  

(15)

By means of statistical analysis it is necessary to determine the degree of definiteness of the researched model, to determine the portion of change of the parameter \(Y\), which describes the model, to determine the adequacy of the regression models, to determine the significance of the regression coefficients \(b_0, b_1, b_2\), to perform analysis of the residues \(\varepsilon = y - \hat{y}\), and then to specify the final form of the model on the base of a comparative analysis of the three proposed models.
Table 2. Degree of definiteness of the researched regression model

<table>
<thead>
<tr>
<th>Parameter/Model</th>
<th>( R = -0.5\Omega )</th>
<th>( R = 0\Omega )</th>
<th>( R = +0.5\Omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coef. of determin. ( R \</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>Q</td>
<td>Cubic</td>
<td>Linear</td>
</tr>
<tr>
<td>0.96</td>
<td>0.99</td>
<td>0.09</td>
<td>0.96</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Coef. of determin. ( R^2 \</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.92</td>
<td>0.99</td>
<td>0.99</td>
<td>0.92</td>
</tr>
<tr>
<td>7</td>
<td>979</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Adjusted ( R^2 \</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.91</td>
<td>0.98</td>
<td>0.98</td>
<td>0.92</td>
</tr>
<tr>
<td>8</td>
<td>973</td>
<td>6</td>
<td>974</td>
</tr>
<tr>
<td>Stad. Error of the Estimate</td>
<td>0.08</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>7</td>
<td>05</td>
<td>5</td>
<td>053</td>
</tr>
</tbody>
</table>

In Table 2 are given the calculated coefficients of determination \( R \) and \( R^2 \) for the three models. The value of the coefficient indicates the percentage of change in the frequency of \( Y \) from tension factor and the remainder to 100% due to other unmanageable factors. Generally, the closer \( R^2 \) is to 1, the better is the selected model’s description of the change of the output value of the investigated factors (Митков, 2011). Variations of the researched variable (Adjusted \( R^2 \)), as well as the standard error in the calculations (Stad. Error of the Estimate), are very small, which confirms the right choice of regression model.

In Table 2 it is seen that the coefficients of determination are weakly influenced by the change in resistance, and at values 0Ω and 0.5Ω are identical. This suggests regression analysis to be performed only maximum and minimum value of change of resistance (load) of the sensors of the converter.

In Figure 3 is shown a regression model at maximum negative load; in Figure 4 it is shown under zero load; and in Figure 5 it is shown at maximum positive load. There are given the lines of regression of the calculated values for linear, quadratic, and cubic models.
quadratic and cubic model. It is seen that the cube model best describes the changes in frequency under the influence of confounding factors.

Table 3. Evaluation of adequacy by Fisher's criterion

<table>
<thead>
<tr>
<th>Parameter/Model</th>
<th>R = -0.5Ω</th>
<th>Linear</th>
<th>Quadratic</th>
<th>Cubic</th>
<th>R = +0.5Ω</th>
<th>Linear</th>
<th>Quadratic</th>
<th>Cubic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion of Fisher F</td>
<td>115,385</td>
<td>192,263</td>
<td>261,246</td>
<td>115,385</td>
<td>192,263</td>
<td>261,246</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical value of Fisher – F&lt;sub&gt;kr&lt;/sub&gt;</td>
<td>4.96</td>
<td>4.46</td>
<td>4.07</td>
<td>4.96</td>
<td>4.46</td>
<td>4.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Evaluation adequacy of the regression models is done using the criterion of Fisher, which is the ratio of residual dispersion in relation to the dispersion of the reproducibility for each model-table 3. The greater the value of the criterion of Fisher, the more adequate the model is [10]. It is necessary, however, to compare initially the calculated value with the critical value of the criterion of Fisher – F<sub>kr</sub> at significance level α = 0.05. If the value is lower than critical, the model is not adequate.

Table 4 gives the values that characterize the significance of the coefficients (parameters) of the model \(b_0, b_1, b_2, b_3\) and the regression coefficients \(\beta_0, \beta_1, \beta_2, \beta_3\).

The calculated value of the criterion of Student, for \(t_i\) – in these cases where \(N\) on number of experiments – is compared with data references particular for the degrees of freedom \(k = N-1\) and \(\gamma = 1-\alpha\), while \(a = 0.05\) – level of significance (Mitrkon, 2011). A verification is made that \(t_i > t_{kr}\). If this inequality is satisfied, that means that the respective coefficient of linear, quadratic or cubic model is significant.

Table 4. Significance of the coefficient of the criterion a Student

<table>
<thead>
<tr>
<th>Parameter/Model</th>
<th>R = -0.5Ω</th>
<th>Linear</th>
<th>Quadratic</th>
<th>Cubic</th>
<th>R = +0.5Ω</th>
<th>Linear</th>
<th>Quadratic</th>
<th>Cubic</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b_0)</td>
<td>0.175</td>
<td>0.012</td>
<td>0.068</td>
<td>0.175</td>
<td>0.102</td>
<td>0.068</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b_1)</td>
<td>0.09</td>
<td>0.016</td>
<td>0.022</td>
<td>0.41</td>
<td>0.074</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b_2)</td>
<td>6,959,1</td>
<td>0.000</td>
<td>1,187,1</td>
<td>0.000</td>
<td>-0.002</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b_3)</td>
<td>0,05</td>
<td>1.408</td>
<td>-0.006</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\beta_0)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\beta_1)</td>
<td>0.963</td>
<td>1.73</td>
<td>2.505</td>
<td>0.963</td>
<td>1.73</td>
<td>2.505</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\beta_2)</td>
<td>-0.8</td>
<td>-2.93</td>
<td>1.408</td>
<td>-2.93</td>
<td>1.408</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\beta_3)</td>
<td>1.408</td>
<td>0.963</td>
<td>-0.8</td>
<td>-2.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t_0)</td>
<td>4,230</td>
<td>3,558</td>
<td>2,967</td>
<td>4,230</td>
<td>3,558</td>
<td>2,967</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t_1)</td>
<td>10,742</td>
<td>9,735</td>
<td>8,805</td>
<td>10,742</td>
<td>9,735</td>
<td>8,805</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t_2)</td>
<td>-4,501</td>
<td>-4,107</td>
<td>3,033</td>
<td>-4,501</td>
<td>-4,107</td>
<td>3,033</td>
<td></td>
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</tr>
<tr>
<td>(t_3)</td>
<td>2,26</td>
<td>2,31</td>
<td>2,36</td>
<td>2,26</td>
<td>2,31</td>
<td>2,36</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 Results:

- The developed model of measurement converter is highly dependent on the inequality of the absolute values of the output voltages of the comparator.
- The coefficient of determination is the highest for the cube model, i.e. it most accurately describes the changes in frequency under the influence of confounding factors.
Assessment evaluation of the adequacy of regression models is performed using the criterion of Fisher. Fisher’s criterion is highest for cube model and does not depend on the load value on the strain gauges.

The coefficient of determination and values of Fisher’s criterion are identical across the whole measuring range. Thus, the high linearity of the converter in the research range is confirmed.

Student’s criterion does not run for negative values of $t_i$. All positive values $t_i$ are significant. This results in a further simplification of regression models and a proof for the significance and relevance of the created models.

The obtained results are the basis for further improvement of the converter and guaranty of the linearity in the whole measurement range.

4 Conclusion

The usage of the regression analysis turns out to be an appropriate decision for testing converter work in different modes. The proven capability to cube model suggests an extremely precise execution of power and measuring circuits.

It is important and necessary condition for the normal operation of the converter is to avoid differences in the output of the comparator tensions, especially due to their strong influence in the equation of transformation and their combined disturbance influence caused by unmanageable factors $w_1, w_2, w_i$.

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